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I further certify that the name of the applicant has been amended to COMMONWEALTH SCIENTIFIC AND INDUSTRIAL RESEARCH ORGANISATION pursuant to the provisions of Section 104 of the Patents Act 1990.

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PROVISIONAL SPECIFICATION FOR THE INVENTION ENTITLED:

An Alarm System for Remote Sensing Equipment

Names and Addresses of Applicants:

Tenix Investments Pty Ltd, an Australian company, ACN 088 304 652, of Level 2 , 100 Arthur Street, North Sydney, New South Wales, 2060, Australia

Commonwealth Scientific and Industrial Research Organisation, a body corporate established by the Commonwealth Science and Industry Research Act 1949 (Cth), of Limestone Avenue, Campbell, Australian Capital Territory, 2612, Australia

Names of Inventors:

Matthew Simmons and Fred Prata and Cirilo Bernardo

This invention is best described in the following statement:

AN ALARM SYSTEM FOR REMOTE SENSING EQUIPMENT

FIELD OF THE INVENTION

The present invention relates generally to remote sensing equipment and, in particular, to management of remote sensing equipment.

BACKGROUND

In recent years, a significant number of commercial jet aircraft have encountered ash clouds emitted from erupting volcanoes, resulting in major safety hazards. Fig. 6 shows such a volcanic eruption. For example, such ash clouds can produce engine failures. This risk is particularly severe for pilots who have not received proper training and information about engines impaired by ash intake.

Silicon compounds within ash clouds can also cause costly damage to aircraft, ranging from abrasion of windows and composite surfaces to engine destruction.

Some volcanic ash particles may be observed by radar, but only if the radar is close enough to the eruption and the particles are large enough. Small ash particles, which can be blown hundreds of miles, do not show up on radar.

One technology that attempts to detect volcanic ash clouds involves large, ground-based 88D ("Nexrad") weather radar units. Such units may be able pick up larger particles that fall out of the ash cloud relatively close to volcanoes. This information may be used to some degree to warn aircraft away from a dangerous area. However, ash clouds that contain fine particles can travel for long distances downwind and pose a significant risk to air traffic. Disadvantageously, such fine particles do not show up on 88D weather radar units. Some government authorities have stated they do not trust aircraft radar alone to provide warning of potentially dangerous ash clouds. The radar is unable to see the small, fine particles.

Satellites have also been used in attempts to detect such volcanic ash. However, existing satellites have a number of problems, including the fact that large areas are covered by a single pixel (thus, an ash cloud may not be detected),

infrequent coverage of areas, inability to see through high clouds, lack of automatic warning, decisions about volcanic activity being highly subjective may involve potentially human error, and using instruments that are designed for other purposes than detecting volcanic ash and sulfur dioxide. One particular problem with satellites is that they often are not directed at an area with an active volcano and may require substantial periods of time and cost to be repositioned to observe volcanic activity. Often, the first indication of the need to redirect the satellite is a report from a jet aircraft that has gone through an ash cloud and encountered engine problems.

Another technology that has been proposed is LIDAR. However, this technology also has a number of disadvantages, including high expense (USD 1 million per 1000m height coverage), being a large device involving large installation area (need mirror telescope), mainly experimental, laser hazard, difficult to image, and having a short range.

SUMMARY

In accordance with an aspect of the invention, there is provided a method of providing an alarm for remote sensing equipment. The method comprises the steps of: calculating temperature differences for a thermal image from the remote sensing equipment; calculating a threshold Gaussian; performing a Gaussian fitting; setting an alarm level for a specified phenomenon; monitoring a histogram of the temperature differences; and generating an alarm condition if the monitored histogram exceeds the alarm level.

The method may further comprise the step of correcting the temperature differences to account for at least one of elevation and atmospheric conditions.

The method may further comprise the step of providing an alarm signal to a user dependent upon the alarm condition.

The method may further comprise the step of performing an action based on the alarm condition.

The method may further comprise the step of capturing the thermal image in a frequency selective manner.

In accordance with another aspect of the invention, there is provided an apparatus for providing an alarm for remote sensing equipment. The apparatus comprises: a module for calculating temperature differences for a thermal image from the remote sensing equipment; a module for calculating a threshold Gaussian; a module for performing a Gaussian fitting; a module for setting an alarm level for a specified phenomenon; a module for monitoring a histogram of the temperature differences; and a module for generating an alarm condition if the monitored histogram exceeds the alarm level.

In accordance with yet another aspect of the invention, there is provided a computer program product having a computer readable medium having a computer program recorded therein for providing an alarm for remote sensing equipment. The computer program product comprises: computer program code for calculating temperature differences for a thermal image from the remote sensing equipment; computer program code for calculating a threshold Gaussian; computer program code for performing a Gaussian fitting; computer program code for setting an alarm level for a specified phenomenon; computer program code for monitoring a histogram of the temperature differences; and computer program code for generating an alarm condition if the monitored histogram exceeds the alarm level.

In accordance with still another aspect of the invention, there is provided a system for providing an alarm for remote sensing equipment. The system comprises: an interface for receiving data comprising temperature differences; a storage unit for storing the data; and a processing unit coupled to the interface and the storage unit. The processing unit is programmed with computer program code to: calculating temperature differences for a thermal image from the remote sensing equipment; calculating a threshold Gaussian; performing a Gaussian fitting; setting an alarm level for a specified phenomenon; monitoring a histogram of the temperature differences; and generating an alarm condition if the monitored histogram exceeds the alarm level.

Other aspects of the apparatus, computer program product, and the system may be implemented in accordance with the method of the first mentioned aspect.

In accordance with a further aspect of the invention, there is provided a system comprising at least one remote sensing equipment and a communications mechanism. Each remote sensing equipment comprises a sensor for generating a thermal image, the thermal image comprising temperature differences, and an alarm module that generates an alarm condition if information based on the thermal image exceeds a predetermined alarm condition. The information comprises statistical data about the thermal image. The communications mechanism communicates the thermal image to a remote location relative to the at least one remote sensing equipment.

The system may further comprise a central monitoring system coupled by the communications mechanism to the at least one remote sensing equipment.

The communications mechanism may comprise a satellite modem. Further, the communications mechanism may comprise a satellite.

The system may further comprise a central monitoring system coupled by a communications network using the communications mechanism to the at least one remote sensing equipment.

The system may further comprise an infrared camera, where the camera houses the sensor and comprises a lens.

The system may further comprise a shutter coupled to the infrared camera.

The system may further comprise a shutter coupled to the infrared camera.

The system may further comprise a filter wheel assembly.

The system may further comprise a computing device coupled to the at least one remote sensing equipment.

Each remote sensing equipment comprises a processing unit programmed to: calculate temperature differences for the thermal image; calculate a threshold Gaussian; perform a Gaussian fitting; set an alarm level for a specified phenomenon; monitor a histogram of the temperature differences; and generate an alarm condition if the monitored histogram exceeds the alarm level.

BRIEF DESCRIPTION OF THE DRAWINGS

Embodiments of the invention are described hereinafter with reference to the drawings, in which:

Fig. 1 is a block diagram of an infrared monitoring system including an alarm system in accordance with an embodiment of the invention;

Fig. 2 is a block diagram of another infrared monitoring system including an alarm system in accordance with another embodiment of the invention;

Fig. 3 is a block diagram of an infrared camera with which embodiments of the invention may be practiced;

Fig. 4 is a flow diagram of an alarm procedure used in remote sensing equipment;

Fig. 5 is a block diagram of a remote sensing system including a satellite used to relay data from the remote sensing equipment to a central monitoring system at a remote location;

Fig. 6 is an image of a volcanic eruption that may contain ash, silicate material, and sulfur dioxide, amongst other things;

Fig. 7A is a color-enhanced, visible infrared image of a cloud containing sulfur dioxide;

Fig. 7B is a sulfur dioxide image produced by the remote sensing equipment from the visible infrared image of Fig. 7A that may trigger the alarm;

Fig. 8 is an image of a camera with a filter wheel and a computing device in accordance with Fig. 3;

Fig. 9 is a two-dimensional plot of an 11-12 μm temperature difference image obtained in ash/SO_2-free conditions viewing with an elevation of 20 degrees above the horizon;

Fig. 10 is a plot of a histogram of the image of Fig. 9 in terms of frequency versus temperature difference;

Fig. 11 is plot of the Gaussian thresholding technique for setting the alarm;

Fig. 12 is a plot of a Gaussian fit to histogram data;

Fig. 13 is a plot of a Gaussian fit to histogram data obtained, showing the t-Gaussian and the decision of whether an alarm is indicated or not;

Fig. 14 is a plot of a Gaussian fit to the histogram data obtained when viewing clear skies near a volcano;

Fig. 15 is a plot of a Gaussian fit to the histogram data obtained when viewing an ash cloud from a volcano, but before intercepting the ash cloud;

Fig. 16 is a plot of a Gaussian fit to the histogram data obtained when viewing an ash cloud from the same volcano as referred to in Fig. 15;

Fig. 17 is a plot of a Gaussian fit to the histogram data obtained when viewing an ash cloud from a volcano, but assuming a viewing elevation angle of 30 degrees;

Figs. 18A and 18B illustrate the variation of the thresholding cutoff with elevation angle; and

Fig. 19 illustrates a general-purpose computer system with which embodiments of the invention may be practiced.

DETAILED DESCRIPTION

Methods, apparatuses, computer program products, and systems are described for providing an alarm for remote sensing equipment. Also described are methods, apparatuses, computer program products, and systems for generating a histogram-based alarm from a thermal image. In the following description, numerous specific details, including particular infrared cameras and sensors, satellite communications systems, network equipment and configurations, filtering techniques, and the like are set forth. However, from this disclosure, it will be apparent to those skilled in the art that modifications and/or substitutions may be made without departing from the scope and spirit of the invention. In other circumstances, specific details may be omitted so as not to obscure the invention.

The methods may be implemented in modules. A module, and in particular its functionality, can be implemented in either software or hardware. In the software sense, a module is a process, program, or portion thereof that usually performs a particular function or related functions. Such software may be implemented in C, C++, JAVA, JAVA BEANS, Fortran, or a combination thereof, for example, but may be implemented in any of a number of other programming

languages/systems, or combinations thereof. In the hardware sense, a module is a functional hardware unit designed for use with other components or modules. For example, a module may be implemented using discrete electronic components, or it may form at least a portion of an entire electronic circuit such as a Field Programmable Gate Arrays (FPGA), Application Specific Integrated Circuit (ASIC), and the like. A physical implementation may also comprise configuration data for a FPGA, or a layout for an ASIC, for example. Still further, the description of a physical implementation may be in EDIF netlisting language, structural VHDL, structural Verilog, or the like. Numerous other possibilities exist. Those skilled in the art will appreciate that the system may also be implemented as a combination of hardware and software modules.

Some portions of the following description are presented in terms of algorithms and representations of operations on data within a computer system or other device capable of performing computations, e.g., a Personal Digital Assistant (PDA). Such algorithmic descriptions and representations may be used by those skilled in the art to convey the substance of their work to others skilled in the art. An algorithm is a self-consistent sequence of steps leading to a desired result. The steps are those requiring physical manipulations of physical quantities. Usually, though not necessarily, these quantities take the form of electrical, magnetic, or electromagnetic signals capable of being stored, transferred, combined, compared, and otherwise manipulated. These signals may be referred to as bits, values, elements, symbols, characters, terms, numbers, or the like.

The above and similar terms are to be associated with the appropriate physical quantities and are merely convenient labels applied to such quantities. Unless specifically stated otherwise, and as apparent from the following, discussions utilizing terms such as "receiving", "calculating", "transferring", "thresholding", "fitting", "executing", "filtering", "generating" "monitoring", "setting", or the like, refer to the actions and processes of a computer system, or a similar electronic device. Such a system or device manipulates and transforms data represented as physical quantities within the registers and memories of the computer system into other data similarly represented as physical quantities within

the computer system registers, memories, or another form of storage, transmission or display devices.

Apparatuses and systems for performing the operations of the methods are also described. Such an apparatus may be specifically constructed for the required purpose, e.g., providing an alarm for remote sensing equipment. Alternatively, the apparatus may comprise a general-purpose computer or another computing device, which may be selectively activated or reconfigured by a computer program read by the computer. The algorithms presented herein are not inherently related to any particular computer or other apparatus; various general-purpose machines may be used with programs.

The embodiments of the invention also relate to a computer program(s) or software, in which method steps may be put into effect by computer code. The computer program is not intended to be limited to any particular programming language, operating environment, and implementation thereof. A variety of programming languages, operating systems, and coding thereof may be used. Moreover, the computer program is not intended to be limited to any particular control flow. There are many other variants of the computer program, which can use different control flows without departing from the scope and spirit of the invention. Furthermore, one or more of the steps of the computer program may be performed in parallel rather than sequentially.

The computer program may be stored on any computer readable medium. The computer readable medium may comprise storage devices, such as magnetic media disks, CD-ROMs, DVDs, flash RAM devices, memory chips, memory cards, magnetic tape, other storage devices and media suitable for interfacing with and being read by a general-purpose computer, and combinations thereof. The computer readable medium may also include a hard-wired medium, such as a local area network or the Internet, or wireless medium, such as an IEEE 802.11 wireless network, a GSM mobile telephone system, PCS, and GPS. The computer program when loaded and executed on such a general-purpose computer effectively results in an apparatus that implements the method steps of the embodiments.

The methods of the embodiments comprise particular control flows. However, different control flows can be practiced without departing from the scope and spirit of the invention. In one particular application, the embodiments of the invention may be employed to detect and discriminate volcanic ash and sulphur dioxide gas in the atmosphere.

I. Remote Sensing System

Fig. 1 is a block diagram of a remote sensing system 100 in accordance with an embodiment of the invention. The system 100 comprises an infrared (IR) camera 110, a shutter 120, remote sensing equipment (RSE) 130, a computing device 140, and a central monitoring system (CMS) 150. The infrared camera 110 may be a spectral imaging longwave (7-14 μm) IR camera. In this embodiment, an IR camera 110 is employed as the sensing equipment, however, other sensors may be practiced without departing from the scope and spirit of the invention. The infrared camera 110 is coupled to the RSE 130. The infrared camera 110 captures infrared images, which can be output by a suitable communications interface. For example, the interface may be an RS-232 interface. Numerous other interfaces including USB and Firewire, for example, may be practiced instead without departing from the scope and spirit of the invention. Still further, communications may be effected using wireless communications (e.g., using Bluetooth. The camera 110 may also control operation of a filter wheel assembly (not shown in Fig. 1). Still further, the camera 110 may measure a focal plane array (FPA) and camera temperature. The IR camera 110 may be based on a 320x240 microbolometer, or equivalent with modifications. The IR camera 110 provides a spectral response across the range 7 to 14 μm and may have a video frame rate of 60 Hz. The IR camera 110 may have a broadband sensor sensitivity of 50 mK or better. With the spectral filter elements, the sensor sensitivity may be better than 200 mK for each filter bandwidth based on 30 consecutive image frames being averaged/co-added.

The IR camera 110 may provide real time averaging (or co-adding) of successive video frames for each position of a filter wheel assembly. The number of averages per filter wheel position may be selectable via a control interface. The

IR camera may store averaged image data on-board, with capacity for 15 or more image files simultaneously, for example. Further details of an infrared camera for use in the alarm system are described hereinafter with reference to Fig. 3.

The system 100 produces two-dimensional (2D) images of a scene in front of the camera, and the data is processed to determine whether or not any volcanic substances are present in the image. The images may be 320x240 pixels, and each pixel is converted to a temperature registered in each of a number (e.g., 5) of channels. While a specific image size is stated, it will be obvious to those skilled in the art that other image sizes (e.g., 800x600 pixels) may be practiced.

A shutter 120 is used in conjunction with the camera 110 and is also coupled to the RSE 130. The shutter 120 may be integrated with the camera 110. The shutter 120 moves in operation with the camera 110. Further, the shutter 120 measures the shutter temperature. The shutter 120 has a suitable communications interface, which may be RS-232. However, other interfaces such as USB and Firewire, for example, may be practiced, as well as wireless communications, such as Bluetooth.

The shutter 120 may be positioned in front of the lens and slightly over-filling the lens, providing a reference temperature field for calibration of the array data. The shutter 120 may incorporate a self-temperature measurement accurate within 100 mK and be designed for uniform temperature across the imaged surface within 200 mK. The shutter 120 may act as a blackbody with emissivity no lower than 0.98. The shutter 120 may rotate fully within or withdraw from the Field of View of the IR camera 110 within a specified time (e.g., 500 milliseconds) upon command via the control interface.

The RSE 130 controls the infrared camera 110, processes image data from the camera 110, and converts the image data, if necessary, to another format suitable for transmission to a remote location. For example, the infrared image data may be converted into a JPEG image file. However, other bitmap formats and other file formats generally may be used without departing from the scope and spirit of the invention. The RSE 130 implements an alarm function that generates an alarm if the RSE 130 in conjunction with the infrared camera 110 and the

shutter 120 detects a phenomenon or given condition. The RSE 130 relays data to a remote data repository and monitoring system 150. This may be done by means of a satellite modem. For example, the modem in the RSE 130 may be an Iridium modem. The link via the iridium modem may permit communications of up to 2.4 Kbps. Further the RSE 130 may comprise two or more communications interfaces for coupling to the camera 110 and the shutter 120. The interface may be RS-232, but other interfaces such as USB and Firewire may be practiced. The RS-232 interfaces may permit communication rates of 115 Kbps, for example. The RSE 130 may provide local web-hosting for the computing device 140 to access via a suitable communications interface.

Each RSE 130 has a sensor, which is preferably an ash detector dead (ADH). The ADH comprises the infrared camera and uses multi-spectral imaging in the long-wave infrared band to discriminate ash particles in the atmosphere from other features, such as water vapor. A single image may be produced that is a fusing of the images from each infrared band, combined to show ash clouds as a different intensity (color) to the background. This single image may converted to an analogue video signal.

The ADH sends this video signal to the RSE and/or its Field Processor Unit (FPU). The ADH can also communicate to the FPU and/or the RSE via a suitable communications link to send an alarm, if ash has been detected. The ADH can also send data describing the detected ash cloud, such as density, altitude, temperature, or other data deemed necessary.

The RSE 130 including the IR camera 110 and the shutter 120 may be deployed in areas where volcanic ash can be detected, such as near volcanoes or surrounding airports. For example, the RSE with the alarm system may be deployed at active volcanoes in countries such as Iceland, Sicily, Japan, Italy and Papua New Guinea, amongst others.

The computing device 140 is coupled to the RSE 130 and may be used to browse the latest images on the RSE 130. Data transfer from the RSE 130 may be controlled using the computing device 140, which may be coupled to the RSE 130 by any suitable communications interface and medium. For example, the RSE 130

and the computing device 140 may communicate by a network, such as a Bluetooth wireless network or an IEEE 802.11b wireless LAN. Communications rates of at least 2 Gbps may be employed using these networks. However, other networks and communications interfaces may be practiced without departing from the scope and spirit of the invention. The computing device 140 may be implemented using a personal digital assistant (PDA), such as a Compaq IPAQ™.

The CMS 150 may comprise a remote central data repository and monitoring system, which stores incoming data from the RSE 130 and may be used to disseminate the incoming data or information based on that data to other locations. The CMS 150 may publish the incoming data to a website, from which the incoming information or information based on the incoming data may be accessed. The CMS 150 may be connected via a satellite link to the RSE 130.

Fig. 2 illustrates a similar system 200 in accordance with another embodiment to that 100 of Fig. 1, but which is practiced without a shutter and has Ethernet communications interfaces coupling the infrared camera 110 to the RSE 130. The Ethernet communications interface may support communications rates of at least 2 Gbps. The infrared camera 210, the RSE 230, the computing device 240, and the CMS 250 are configured the same and perform the same functionality as those of Fig. 1, without requiring the shutter and associated functionality. The camera 110, 210 is described hereinafter in greater detail with reference to Fig. 3.

Fig. 5 is a further diagram illustrating a configuration 500 of the system with which the alarm system may be practiced. Several RSE 510, 512, 514 each having an infrared camera and an alarm system communicate with a satellite 520 to transmit data and alarm conditions to a remote location. The satellite 520 downloads the information to an internet service provider (ISP) 530, which transmits the information via the Internet 532 to another ISP 534. The CMS 540 can receive the information and communicate with the RSEs via the ISP 534.

II. Infrared Camera

Fig. 3 is a block diagram of an infrared camera 300 with which embodiments of the invention may be practiced. The camera 300 comprises a housing 310, a lens 320, and an infrared sensor array 330. The lens is made of

infrared selective media, e.g., germanium. The filter wheel assembly 330 may be used in combination with the infrared camera 300. The filter wheel assembly 330 comprises several infrared selective filters 332 ... 334. Each of the filters 332 ... 334 are frequency selective. For example, the filter 332 may transmit infrared energy having a wavelength of approximately 10 μm, while the filter 334 may transmit infrared energy having a wavelength of approximately 8 μm. Infrared rays 340, 342 generated by a cloud 380, for example, are incident on the lens 320, which projects the rays on the filter 334. The cloud 380 may comprise ash, silicate matter, and/or sulfur dioxide (SO_2). While two specific filters are referred to, it will be apparent to those skilled in the art that other numbers of filters may be practiced with different wavelengths (e.g., 7.3 μm). The filter 334 transmits components of the infrared energy in a pass band to the infrared array 340, while other components of the infrared energy out of the pass band are rejected.

The filter wheel assembly 330 provides a motorized drive capable of rotating to successive filter positions dependent upon the number of filters. For example, if there are five filters, the filters are nominally 72 degrees apart. The filter element size should be sufficient to fully span the field of view of the detector array. In one embodiment, the (five) filter elements have the following center wavelengths and bandwidths:

Element	Centre Wavelength	Filter Bandwidth (50%)
1	Broadband	7-14 μm
2	8.6 μm	+/- 0.25μm
3	10 μm	+/- 0.5 μm
4	11 μm	+/- 0.5 μm
5	12 μm	+/- 0.5 μm

If the filter element design is such that reflective artefacts may be produced in the images, the design of the filter wheel assembly 330 may provide for a slight angle of tilt to prevent this occurrence.

The channels may select radiation over a narrowband (0.5-1.0 μm wide) with central wavelengths carefully chosen to permit maximum discrimination of ash or SO_2. Detection and discrimination of substances in the image scene is

achieved by comparing images at different central wavelengths (different channels) taken a few seconds apart. These difference images may be used to identify ash, or SO_2, or both.

The infrared sensor array 340 detects incident infrared energy and provides infrared image data to a processing unit 350, which implements an alarm function. Fig. 7A shows a visible infrared image of a cloud containing sulfur dioxide 710. Fig. 7B shows an image of the sulfur dioxide produced by the remote sensing equipment from the visible infrared image of Fig. 7A that may trigger an alarm. The processing unit 350 may form part of the RSE 130 of Fig. 1 or 2. The processing unit 350 provides an alarm signal, if an alarm condition is detected, to an alarm output 360. The alarm output 360 may be an audible, visible, or other alarm signal or data. The alarm process is depicted in Fig. 4.

As noted hereinbefore, difference images are used to identify ash or SO_2. Rapid identification of substances within the image scene is required. To eliminate undesirable effects, i.e., incorrectly assigning a pixel as ash/SO_2 and incorrectly identifying a pixel as clear when the pixel is ash/SO_2, the statistically based alarm algorithm recognizes that anomalous pixels may occur. These pixels arise because of noise, lack of sensitivity, poor calibration, degradation of a focal plane array detector (increase in the number of bad pixels), or because of unusual atmospheric phenomena. The occurrence of these anomalous pixels is largely random, but may arise in a fixed pattern. In either case, their underlying spatial structure is different to that expected from the signal due to an ash/SO_2 cloud, which follows the normal or Gaussian distribution. The infrared camera may view the scene in any specified viewing geometry. The majority of viewing cases are above the horizon. The detection algorithm uses thresholds that depend on the viewing elevation of the camera.

Fig. 8 is an image of an actual infrared camera 800 mounted on a tripod in accordance with the camera 300, comprising a camera housing 810, a lens 820, and a filter wheel assembly 830. The camera 800 is coupled to a computing device 840, e.g., a Compaq IPAQ™.

III. Alarm Process

The infrared camera images are processed to determine whether or not significant numbers of pixels indicate that ash/SO_2 has been detected. The image may comprise 320x240 pixels, each of which could detect ash/SO_2. Noise and lack of sensitivity or calibration errors and camera-body temperature fluctuations may induce anomalous signals in a captured image. In general, the structure of these anomalies is quite different to that expected from an ash cloud. However, on a pixel-by- pixel basis, it may not be possible to determine whether the signal is due to a camera anomaly or a real ash/SO_2 signature. The structure in the images may be used to set a threshold or alarm to indicate the presence of ash/SO_2.

Fig. 9 shows an image obtained in ash/SO_2-free conditions viewing with an elevation of 20 degrees above the horizon. The color scale on this image indicates a temperature range from -15 K to 10 K, with red pixels at the upper end of the vertical scale having the most positive temperature difference. To highlight the region where most ambiguity might exist, a grey-scale showing temperatures from -0.5 K to 0.5 K is included within the main color scale. Thus, grey-colored pixels 930 in the temperature difference image may be regarded as marginal, in terms of detectability. In this image, there are some grey-colored pixels 930, but the majority of the pixels are yellow 910, green to blue 920 indicating negative temperature differences and hence normal conditions (i.e. clear skies or water/ice meteorological clouds).

Fig. 10 depicts a two-dimensional histogram of the image shown in Fig. 9. The same temperature range and color scale are used for the histogram. From theoretical and modeling calculations, pixels that are ash contaminated are expected to have positive differences, but their actual value depends on viewing conditions, particularly the viewing elevation, and also the amount of water vapor in the path. A threshold value of 0 K for ash may be used under most conditions. As the field-of-view of the infrared camera of Fig. 3 is roughly 24 degrees in the vertical direction, some parts of the image view land surfaces. The histogram has prominent peaks at roughly 1 K and 5 K, which correspond to clouds and clear skies, respectively. In this case, the least negative peak has a tail that includes some positive pixels. In the corresponding image, these pixels are viewing features

that are low on the horizon and include ground targets. Such 'anomalies' are difficult to isolate in an automated manner and may give rise to false alarms if a straightforward pixel thresholding technique is employed. For some data, anomalies also arise in conditions where there is ash mixed in with significant amounts of water vapor or cloud. In this context, these pixels may be considered as important to identify correctly. The alarm process is described in greater detail hereinafter.

Figs. 18A and 18B illustrate the variation of the thresholding cutoff with elevation angle. Elevation angle is measured to correct for various atmospheric effects.

The alarm process is statistically based to automatically determine whether an image has detected ash/SO_2. Due to the nature of the problem, there is often a distribution of pixels that can be flagged as ash, within an image that has many pixels that are definitely ash, or definitely not ash. In addition, because of the likelihood that pixels contain mixtures, a simple threshold and binary decision process may not be appropriate.

Fig. 4 illustrates a process 400 of providing an alarm function for remote sensing equipment to detect a phenomenon or condition. Processing commences in step 408. In step 410, infrared (IR) temperatures are collected in selected bandwidths using the camera 300 and a filter wheel assembly 330. In step 412, temperature differences are calculated. In step 414, the temperature differences are corrected for elevation and atmospheric conditions. In step 416, a threshold Gaussian is calculated. For example, water vapor or sea spray may be higher at lower elevation angles, which can cause errors in the gathered image and resultant alarm. In step 418, Gaussian fitting is performed. This is described hereinafter in greater detail in the following section. In step 420, the high/low level alarm is set for ash, SO_2, etc. In step 422, data histograms are monitored. In step 424, an alarm is provided to an internal or external user. In step 426, an alarm-based action is taken, provided an alarm condition is triggered/detected. Processing then continues at step 422.

The alarm may be set by the user at different levels and is adapted to various conditions to avoid high false alarm rates and to conform to the particular user needs.

III. Gaussian Fitting

The 2D histogram shown in Fig. 10 comprises two prominent peaks with a spread of pixels around these peaks. If the infrared camera viewed a target of constant temperature (e.g. a uniform cloud or the clear sky), the resulting difference image is non-uniform, because the camera has a wide field-of-view and there is water vapor absorption along the differing paths to the target. In practice, the sky would not likely present a uniform target, and the cloud is even less likely to be uniform. The combination of these effects leads to a natural spread in the histogram of the temperature differences, with a central peak corresponding to the mode temperature difference. For a relatively uniform scene, the peak is high and the spread (or standard deviation of the distribution) is low.

A natural choice to model this kind of distribution is the normal distribution or Gaussian distribution. The Gaussian distribution in mathematical terms is:

$$G(\Delta T) = Ao \exp\left\{-\frac{(\Delta T - \mu\Delta T)}{\sigma\Delta T}\right\}^2, \qquad (1)$$

where ΔT is the temperature difference, $\mu\Delta T$ is the mean temperature difference, $\sigma\Delta T$ s the standard deviation, and Ao is the maximum frequency, which occurs when $\Delta T = \mu\Delta T$. Each of the peaks (i = 1 ... n) within the frequency distribution (histogram plot) is assumed to be centered at $\mu\Delta T,i$ with a spread of $\sigma\Delta T,i$. A set of Gaussian distributions is fitted to the frequency distribution data and the parameters, Ao,i, $\mu\Delta T,i$, and $\sigma\Delta T,i$ derived. The linear combination of these distributions is the model-fit to the data.

Fig. 11 is two-dimensional plot 1100 of the Gaussian thresholding technique for setting the alarm. The blue-grey region 1120 contains pixels that fall within the overlap between the threshold Gaussian; the orange-colored region 1110 shows the pixels that are counted as ash pixels.

The fit for the histogram data shown in Fig. 10 is shown in Fig. 12. Three Gaussians maybe used in the fit:

Parameter	i=1	i=2	i=3
$A_{0,i}$	74.2%	24.9%	0.9%
$\mu_{\Delta T,i}$	−4.24 K	−0.84 K	−0.67 K
$\sigma_{\Delta T,i}$	±1.49 K	±0.33 K	±0.08 K

The fit to the distribution, although not perfect, is sufficient for setting the alarm for the image. The alarm technique proceeds by setting a threshold Gaussian with a mean and standard deviation derived from modelling, and comparing this with the n-Gaussian data-fit. The region between the pixels bounded by the threshold Gaussian mean value and the overlap region between the two Gaussians (the threshold and the data-fit) are calculated. This area (or number of pixels) is subtracted from the number of pixels that exceed the threshold Gaussian (t-Gaussian) mean value and lie within the data-fit Gaussian (see Fig. 11).

The ratios are:

$$Ri = \frac{Ao,i}{\sum_{j=1}^{n} Ao,j}\left(\frac{Pi - Po,i}{Pi}\right), \qquad (2)$$

where $P_{o,i}$ is the number of overlap pixels for Gaussian i, P_i is the number of pixels that exceed the threshold mean, and $A_{o,i}$ are the maxima for the Gaussian fits. Normalising by the maximum ensures that more weight is given to distributions that have well-defined and dominant peaks.

To demonstrate how the alarm works, use is made of data obtained from field measurements made at active volcanoes when viewing an ash/SO_2 cloud, as well as clear and cloudy skies (i.e. ash/ SO_2 free conditions). Thresholds (cut-off's) that depend on viewing elevation are set, and these thresholds correspond to the mean of the threshold Gaussian. The spread or standard deviation of the t-Gaussian also depends on the elevation angle. Values for these may be determined through radiative transfer modeling. The precise value depends on the atmospheric conditions: principally, the amount of water vapor present in the atmosphere.

Fig. 12 shows a histogram obtained in ash/SO_2-free conditions. There are two prominent peaks (at ΔT= -4.24 K and ΔT= -0.84 K) in the histogram and one minor peak (at ΔT= -0.67 K). The temperature difference in this and subsequent images corresponds to 11 μm - 12 μm temperature differences. The temperature difference used discriminates volcanic ash; for SO_2 gas, the shorter wavelength may be changed to 8.6 μm. A cut-off value of -1.0 K is shown and the Gaussian-fit (using n=3) is superimposed over the data (green line 1210). In this case, the data are well described by three Gaussians. The majority of the pixels (74%) fall within the Gaussian distribution with mean = -4.24 K and standard deviation = ±1.49 K.

Fig. 13 shows the same data as in Fig. 12, but with the t-Gaussian 1310 drawn and the probability measures for each of the three Gaussians fitted to the histogram data. The t-Gaussian 1310 has a mean of 0 K and a spread of ±2 K. No alarms are generated from these data, because no pixel in the histogram lies beyond the cut-off value fall outside the spread of the threshold Gaussian. No alarm signal would be generated for this image.

A second example is shown in Figs. 14 and 15, also obtained in clear/cloudy skies (Figs. 14 and 15, respectively). In this case, the camera viewed the scene at a low elevation angle of 10 degrees. Three Gaussians fit the data well and the t-Gaussian has mean 0 K and standard deviation of ±2 K. In this case, the Gaussian that includes most pixels (>94 %, $\mu\Delta T$ = +0.26 K) generates a 2 % alarm. The low alarm is a consequence of the fact that many of the pixels that exceed the cut-off value (0 K) lie within the spread of the threshold Gaussian and hence are statistically indistinguishable from the expected noise characteristics of the thermal imagery.

A third example is shown in Fig. 16. The imagery in this case has been acquired while the camera viewed an ash-laden cloud from a volcano. Three Gaussian distributions fit the data well. The most significant peak at $\mu\Delta T$ = +5.45 K (>91 %) generates a 67% alarm. The alarm is less than 91 % because some of the pixels within the Gaussian still lie with the spread of the t-Gaussian and there are ≈ 10% of the pixels included within the second and third Gaussians. The

sensitivity of the alarm to the position of the threshold Gaussian is illustrated in Fig. 17, where the same data is used with a t-Gaussian appropriate for a 30 degree viewing elevation. The t-Gaussian has a mean of -0.5 K and a spread of ±1 K.

One application of such an alarm system for remote sensing equipment is in ground-based detector systems to warn pilots, and airports, of potential volcanic ash clouds in flight areas. The embodiments of the invention permit automatic warning of volcanic activity using ground-based instrumentation and systems for continuous monitoring of volcanic activity. The systems are able to automatically detect ash, SO_2, or both. In some cases, the alarm system feeds back the alarm indication into air safety networks, and in other cases may be used for a variety of scientific and civil defense purposes.

While sensors for ash/SO_2 have been described, the alarm system may also be suitable for detection of clear air turbulence and hazards such as low-level wind shear, as well as for terrain avoidance. The ash detection method can distinguish between volcanic clouds and normal water and ice clouds. Ash clouds are virtually invisible to radar and are not visible at nighttime.

While the embodiments of the invention have been described with reference to ground-based systems, the alarm system may be practiced in other environments. For example, such an alarm system might be employed in aircraft generally, research aircraft, on-board ash detection for commercial and military jets, other hyper spectral applications, and UAV applications.

Additional applications for the alarm system in remote sensing equipment includes following: SO_2 monitoring from natural and man-made sources, dust monitoring, defense applications, security (e.g., border patrol), hyper spectral applications (bush-fires, agriculture), bushfire monitoring, amongst others.

IV. Computer Implementation

The methods according to the embodiments of the invention may be practiced using one or more general-purpose computer systems, handheld devices, and other suitable computing devices, in which the processes described with reference to Figs. 1-18 may be implemented as software, such as an application program executing within the computer system or a handheld device. For

example, a PDA is a computer system that may be used to practice the invention. In particular, instructions in the software that are carried out by the computer effect the steps in the method of providing an alarm for remote sensing equipment are effected, at least in part. Software may include one or more computer programs, including application programs, an operating system, procedures, rules, data structures, and data. The instructions may be formed as one or more code modules, each for performing one or more particular tasks. The software may be stored in a computer readable medium, comprising one or more of the storage devices described below, for example. The computer system loads the software from the computer readable medium and then executes the software.

Fig. 19 depicts an example of a computer system 1900 with which the embodiments of the invention may be practiced. A computer readable medium having such software recorded on the medium is a computer program product. The use of the computer program product in the computer system may effect an advantageous apparatus for providing a location estimate of a wireless mobile station in accordance with the embodiments of the invention.

Fig. 19 graphically depicts the computer system 1900, comprising a computer 1950, a display 1910, and an input device 1930, i.e., a keypad or keyboard. Fig. 19 illustrates the computer system 1900 in block diagram form, coupled to a network. An operator may use the keyboard 1930 and/or a pointing device such as the mouse 1932 (or touchpad, for example) to provide input to the computer 1950. This may be required for example to set up the alarm system during installation at a remote location. The computer system 1900 may have any of a number of output devices, including line printers, laser printers, plotters, and other reproduction devices connected to the computer. The computer system 1900 can be connected to one or more other computers via a communication interface 1964 using an appropriate communication channel 1940 such as a modem communications path, a USB communications interface, or the like. One example of a modem is an Iridium modem for communications with a satellite. The computer network 1920 may comprise a local area network (LAN), a wide area network (WAN), an Intranet, and/or the Internet, for example.

The computer 1950 may comprise a processing unit 1966 (e.g., one or more central processing units) 1966, memory 1970 which may comprise random access memory (RAM), read-only memory (ROM), or a combination of the two, input/output (IO) interfaces 1972, a graphics interface 1960, and one or more storage devices 1962. The storage device(s) 1962 may comprise one or more of the following: a floppy disc, a hard disc drive, a magneto-optical disc drive, CD-ROM, DVD, a data card or memory stick, flash RAM device, magnetic tape or any other of a number of non-volatile storage devices well known to those skilled in the art. While the storage device is shown directly connected to the bus in Fig. 19, such a storage device may be connected through any suitable interface, such as a parallel port, serial port, USB interface, a Firewire interface, a wireless interface, a PCMCIA slot, or the like. For the purposes of this description, a storage unit may comprise one or more of the memory 1970 and the storage devices 1962 (as indicated by a dashed box surrounding these elements in Fig. 19).

Each of the components of the computer 1950 is typically connected to one or more of the other devices via one or more buses 1980, depicted generally in Fig. 19, that in turn comprise data, address, and control buses. While a single bus 1980 is depicted in Fig. 19, it will be well understood by those skilled in the art that a computer or other electronic computing device, such as a PDA, may have several buses including one or more of a processor bus, a memory bus, a graphics card bus, and a peripheral bus. Suitable bridges may be utilized to interface communications between such buses. While a system using a CPU has been described, it will be appreciated by those skilled in the art that other processing units capable of processing data and carrying out operations may be used instead without departing from the scope and spirit of the invention.

The computer system 1900 is simply provided for illustrative purposes, and other configurations can be employed without departing from the scope and spirit of the invention. Computers with which the embodiment can be practiced comprise IBM-PC/ATs or compatibles, laptop/notebook computers, one of the Macintosh (TM) family of PCs, Sun Sparcstation (TM), a PDA such as a Compaq IPAQ™, a workstation or the like. The foregoing are merely examples of the types

of devices with which the embodiments of the invention may be practiced. Typically, the processes of the embodiments, described hereinafter, are resident as software or a program recorded on a hard disk drive as the computer readable medium, and read and controlled using the processor. Intermediate storage of the program and intermediate data and any data fetched from the network may be accomplished using the semiconductor memory.

In some instances, the program may be supplied encoded on a CD-ROM or a floppy disk, or alternatively could be read from a network via a modem device connected to the computer, for example. Still further, the software can also be loaded into the computer system from other computer readable medium comprising magnetic tape, a ROM or integrated circuit, a magneto-optical disk, a radio or infra-red transmission channel between the computer and another device, a computer readable card such as a PCMCIA card, and the Internet and Intranets comprising email transmissions and information recorded on websites and the like. The foregoing is merely an example of relevant computer readable mediums. Other computer readable mediums may be practiced without departing from the scope and spirit of the invention.

A small number of embodiments of the invention regarding methods, apparatuses, computer program products, and systems for providing an alarm for remote sensing equipment have been described. Also, methods, apparatuses, computer program products, and systems for generating a histogram-based alarm from a thermal image have been described. In the light of the foregoing, it will be apparent to those skilled in the art in the light of this disclosure that various modifications and/or substitutions may be made without departing from the scope and spirit of the invention.

The claims defining the invention are as follows:

1. A method of providing an alarm for remote sensing equipment, said method comprising the steps of:

calculating temperature differences for a thermal image from said remote sensing equipment;

calculating a threshold Gaussian;

performing a Gaussian fitting;

setting an alarm level for a specified phenomenon;

monitoring a histogram of said temperature differences; and

generating an alarm condition if said monitored histogram exceeds said alarm level.

2. The method according to claim 1, further comprising the step of correcting said temperature differences to account for at least one of elevation and atmospheric conditions.

3. The method according to claim 1, further comprising the step of providing an alarm signal to a user dependent upon said alarm condition.

4. The method according to claim 1, further comprising the step of performing an action based on said alarm condition.

5. The method according to claim 1, further comprising the step of capturing said thermal image in a frequency selective manner.

6. An apparatus for providing an alarm for remote sensing equipment, said apparatus comprising:

means for calculating temperature differences for a thermal image from said remote sensing equipment;

means for calculating a threshold Gaussian;

means for performing a Gaussian fitting;

means for setting an alarm level for a specified phenomenon;

means for monitoring a histogram of said temperature differences; and

means for generating an alarm condition if said monitored histogram exceeds said alarm level.

7. The apparatus according to claim 6, further comprising means for correcting said temperature differences to account for at least one of elevation and atmospheric conditions.

8. The apparatus according to claim 6, further comprising means for providing an alarm signal to a user dependent upon said alarm condition.

9. The apparatus according to claim 6, further comprising means for performing an action based on said alarm condition.

10. The apparatus according to claim 6, further comprising means for capturing said thermal image in a frequency selective manner.

11. A computer program product having a computer readable medium having a computer program recorded therein for providing an alarm for remote sensing equipment, said computer program product comprising:

computer program code means for calculating temperature differences for a thermal image from said remote sensing equipment;

computer program code means for calculating a threshold Gaussian;

computer program code means for performing a Gaussian fitting;

computer program code means for setting an alarm level for a specified phenomenon;

computer program code means for monitoring a histogram of said temperature differences; and

computer program code means for generating an alarm condition if said monitored histogram exceeds said alarm level.

12. The computer program product according to claim 11, further comprising computer program code means for correcting said temperature differences to account for at least one of elevation and atmospheric conditions.

13. The computer program product according to claim 11, further comprising computer program code means for providing an alarm signal to a user dependent upon said alarm condition.

14. The computer program product according to claim 11, further comprising computer program code means for performing an action based on said alarm condition.

15. The computer program product according to claim 11, further comprising computer program code means for capturing said thermal image in a frequency selective manner.

16. A system for providing an alarm for remote sensing equipment, comprising:

an interface for receiving data comprising temperature differences;

a storage unit for storing said data; and

a processing unit coupled to said interface and said storage unit, said processing unit programmed with computer program code to:

calculating temperature differences for a thermal image from said remote sensing equipment;

calculating a threshold Gaussian;

performing a Gaussian fitting;

setting an alarm level for a specified phenomenon;

monitoring a histogram of said temperature differences; and

generating an alarm condition if said monitored histogram exceeds said alarm level.

17. The system according to claim 16, wherein said processing unit is programmed to correct said temperature differences to account for at least one of elevation and atmospheric conditions.

18. The system according to claim 16, wherein said processing unit is programmed to provide an alarm signal to a user dependent upon said alarm condition.

19. The system according to claim 16, wherein said processing unit is programmed to perform an action based on said alarm condition.

20. The system according to claim 16, further comprising a sensor to capture said thermal image in a frequency selective manner.

21. A system, comprising:

at least one remote sensing equipment, each comprising:

a sensor for generating a thermal image, said thermal image comprising temperature differences; and

an alarm module that generates an alarm condition if information based on said thermal image exceeds a predetermined alarm condition, said information comprising statistical data about said thermal image; and

a communications mechanism for communicating said thermal image to a remote location relative to said at least one remote sensing equipment.

22. The system according to claim 21, further comprising a central monitoring system coupled by said communications mechanism to said at least one remote sensing equipment.

23. The system according to claim 22, wherein said communications mechanism comprises a satellite modem.

24. The system according to claim 22, wherein said communications mechanism comprises a satellite.

25. The system according to claim 21, further comprising a central monitoring system coupled by a communications network using said communications mechanism to said at least one remote sensing equipment.

26. The system according to claim 21, further comprising an infrared camera, said camera housing said sensor and comprising a lens.

27. The systems according to claim 26, further comprising a shutter coupled to said infrared camera.

28. The system according to claim 26, further comprising a shutter coupled to said infrared camera.

29. The system according to claim 26, further comprising a filter wheel assembly.

30. The system according to claim 21, further comprising a computing device coupled to said at least one remote sensing equipment.

31. The system according to claim 21, wherein said at least one remote sensing equipment comprises a processing unit programmed to:

calculate temperature differences for said thermal image;

calculate a threshold Gaussian;

perform a Gaussian fitting;

set an alarm level for a specified phenomenon;

monitor a histogram of said temperature differences; and

generate an alarm condition if said monitored histogram exceeds said alarm level.

DATED this Twenty-ninth Day of September, 2003

Tenix Investments Pty Ltd

Commonwealth Scientific and Industrial Organisation

Patent Attorneys for the Applicants

SPRUSON & FERGUSON

AN ALARM SYSTEM FOR REMOTE SENSING EQUIPMENT

ABSTRACT

Methods, apparatuses, computer program products, and systems are described for providing an alarm for remote sensing equipment. One system comprises at least one remote sensing equipment and a communications mechanism. The remote sensing equipment each comprises a sensor for generating a thermal image and an alarm module. The thermal image comprises temperature differences. The alarm module generates an alarm condition if information based on the thermal image exceeds a predetermined alarm condition. The information comprises statistical data about the thermal image. The communications mechanism communicates the thermal image to a remote location relative to the at least one remote sensing equipment.

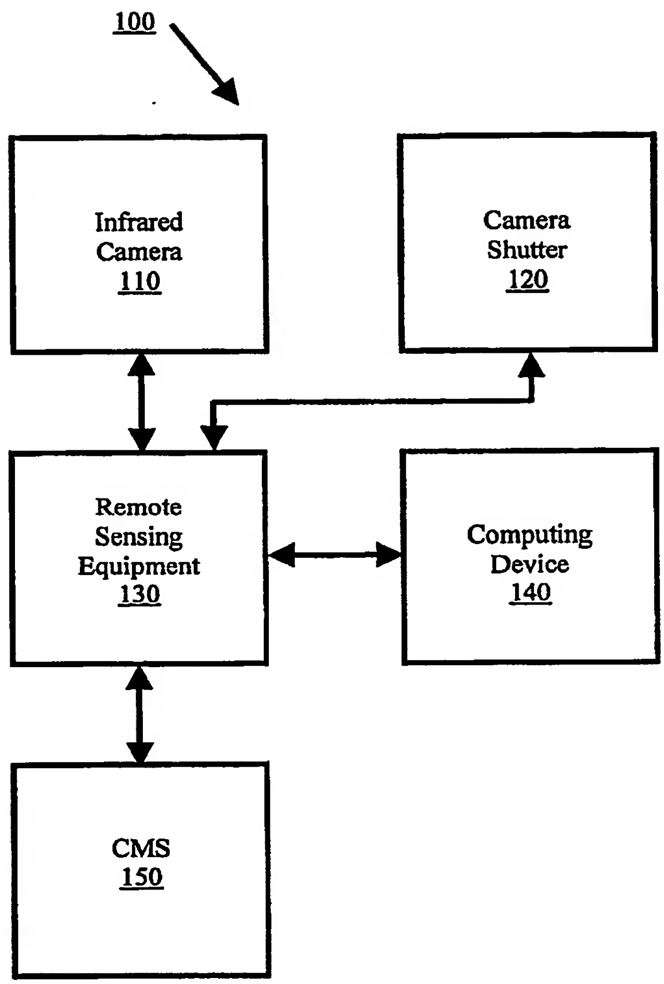
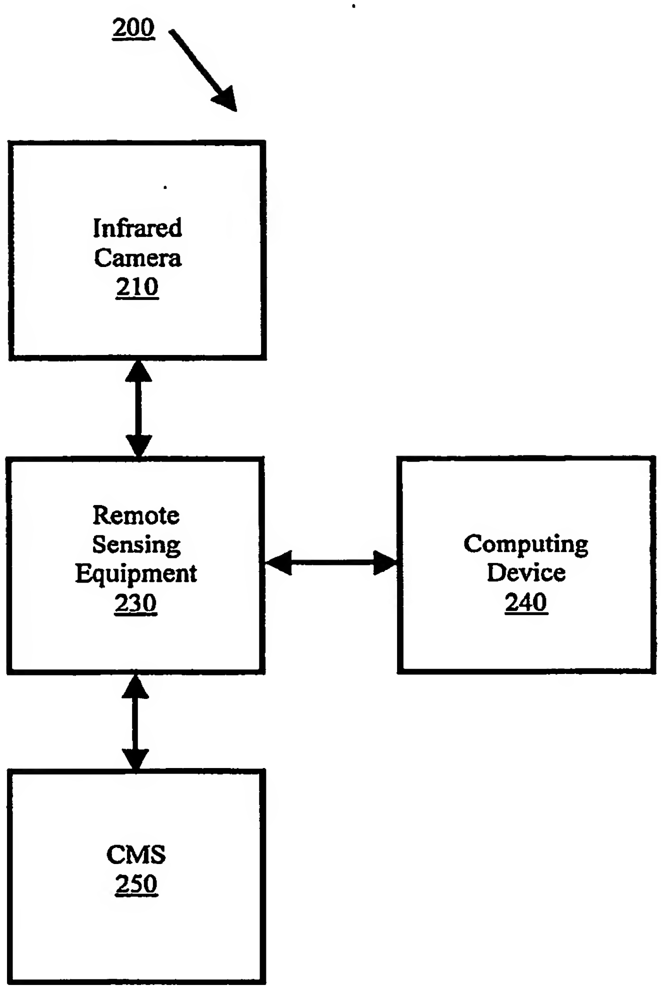

100
Infrared Camera 110
Camera Shutter 120
Remote Sensing Equipment 130
Computing Device 140
CMS 150

FIG. 1



200
Infrared Camera 210
Remote Sensing Equipment 230
Computing Device 240
CMS 250

FIG. 2

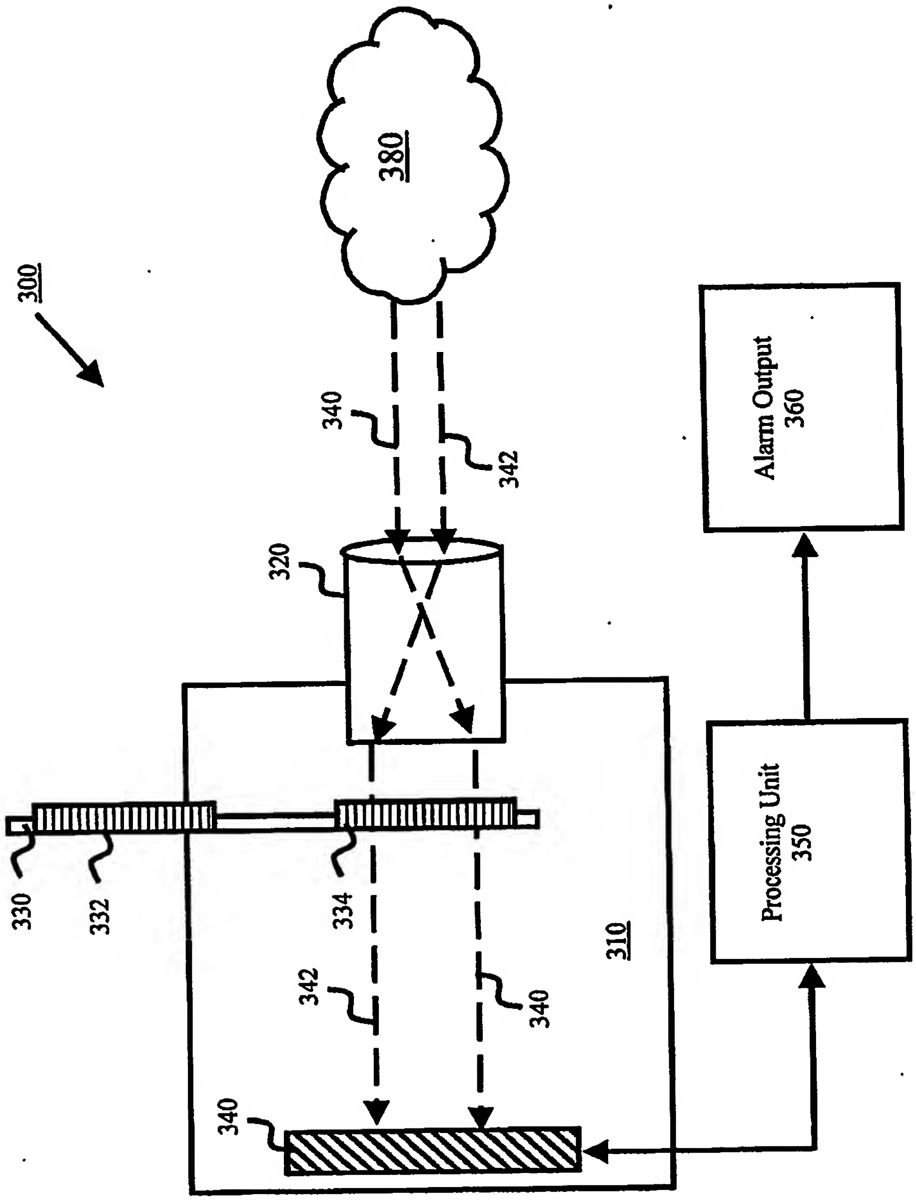

300
380
340
342
320
330
332
334
342
340
340
310
Alarm Output
360
Processing Unit
350

FIG. 3

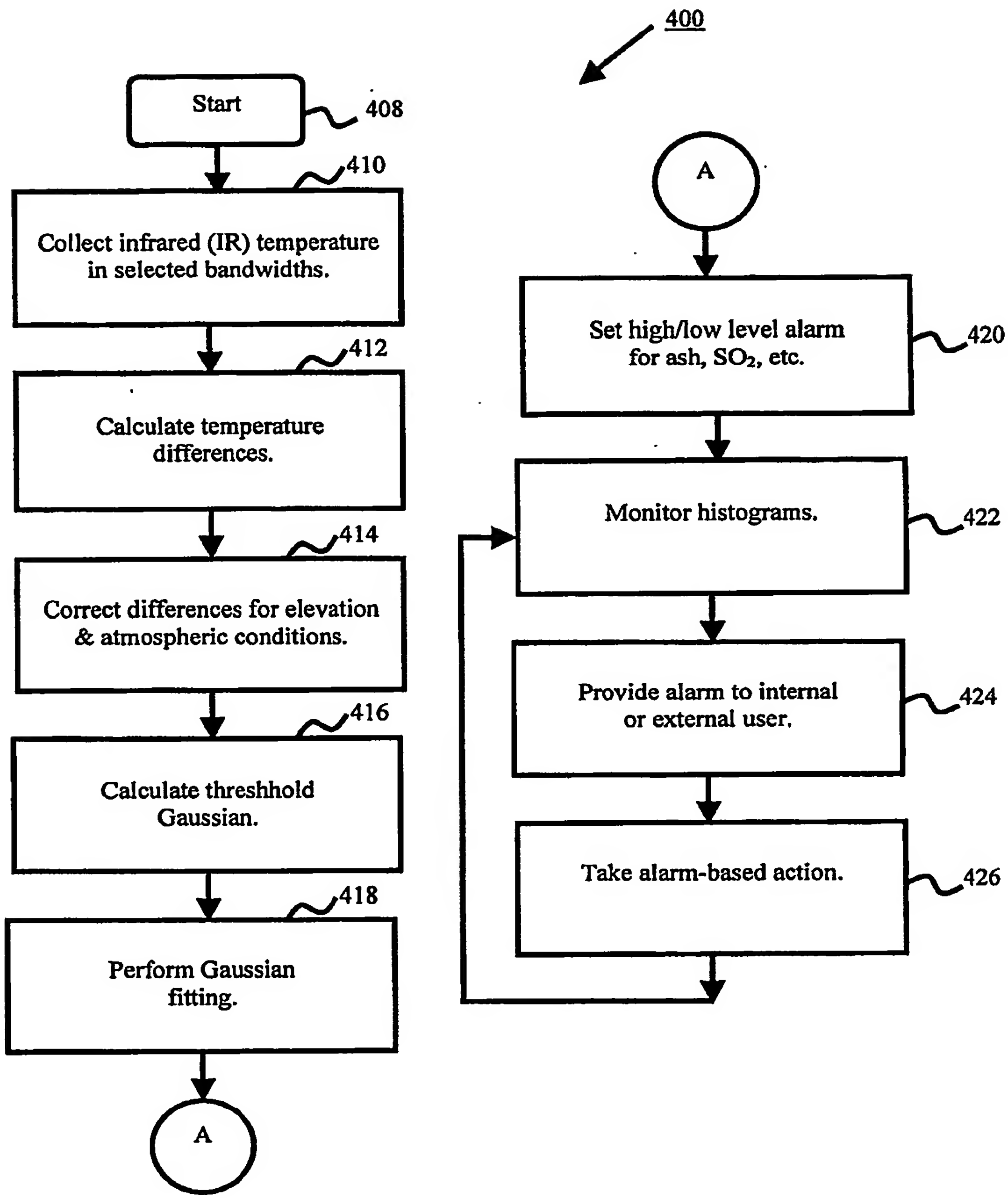

400
Start
408
410
Collect infrared (IR) temperature in selected bandwidths.
412
Calculate temperature differences.
414
Correct differences for elevation & atmospheric conditions.
416
Calculate threshhold Gaussian.
418
Perform Gaussian fitting.
A
A
Set high/low level alarm for ash, SO2, etc.
420
Monitor histograms.
422
Provide alarm to internal or external user.
424
Take alarm-based action.
426

FIG. 4

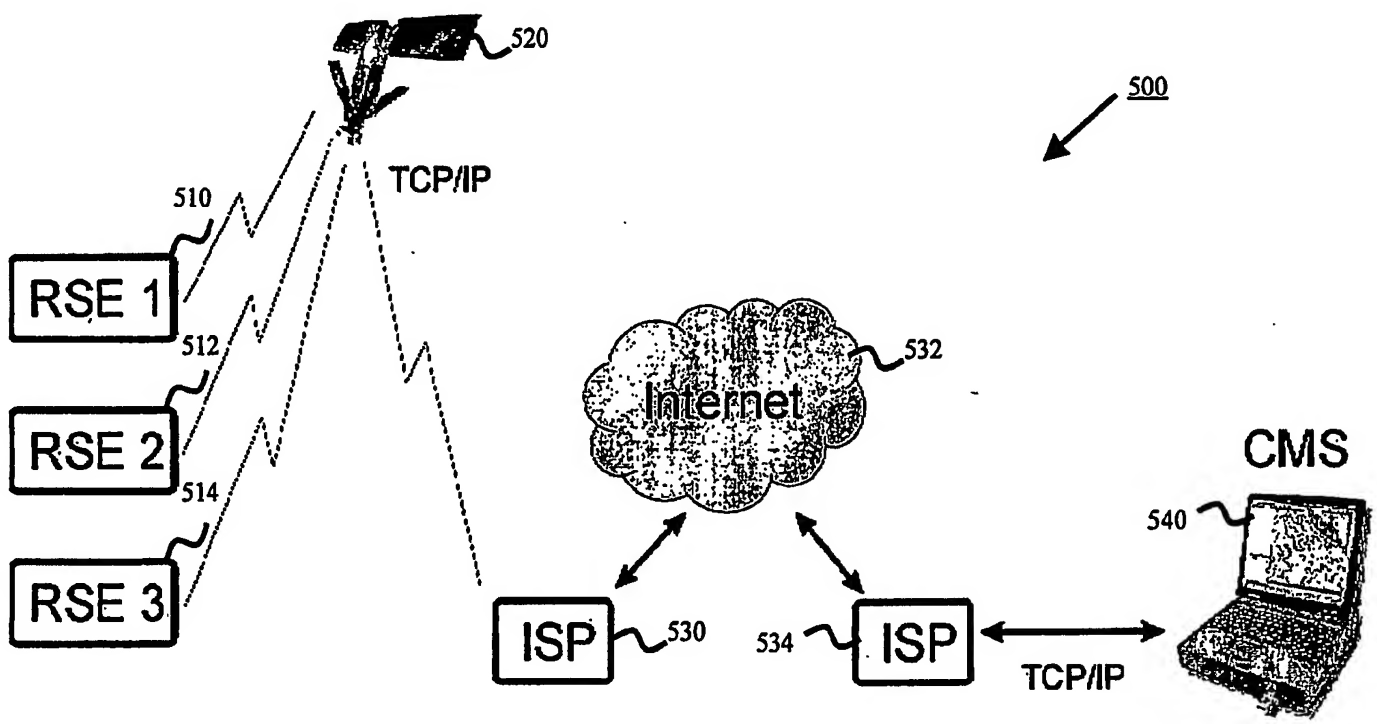

500
520
TCP/IP
510
RSE 1
512
RSE 2
514
RSE 3
Internet
532
ISP
530
534
ISP
TCP/IP
CMS
540

FIG. 5

FIG. 6

FIG. 7A

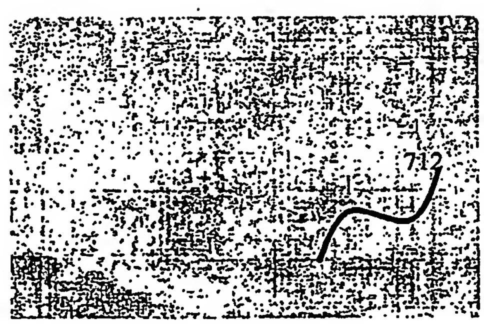


FIG. 7B

800

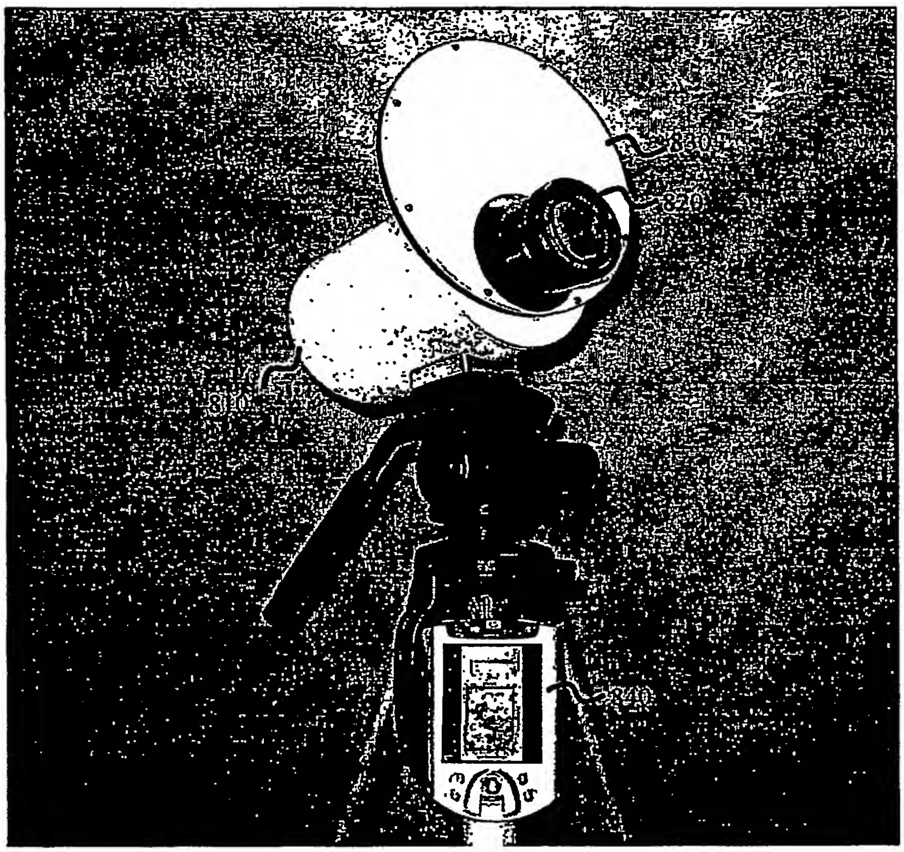


FIG. 8

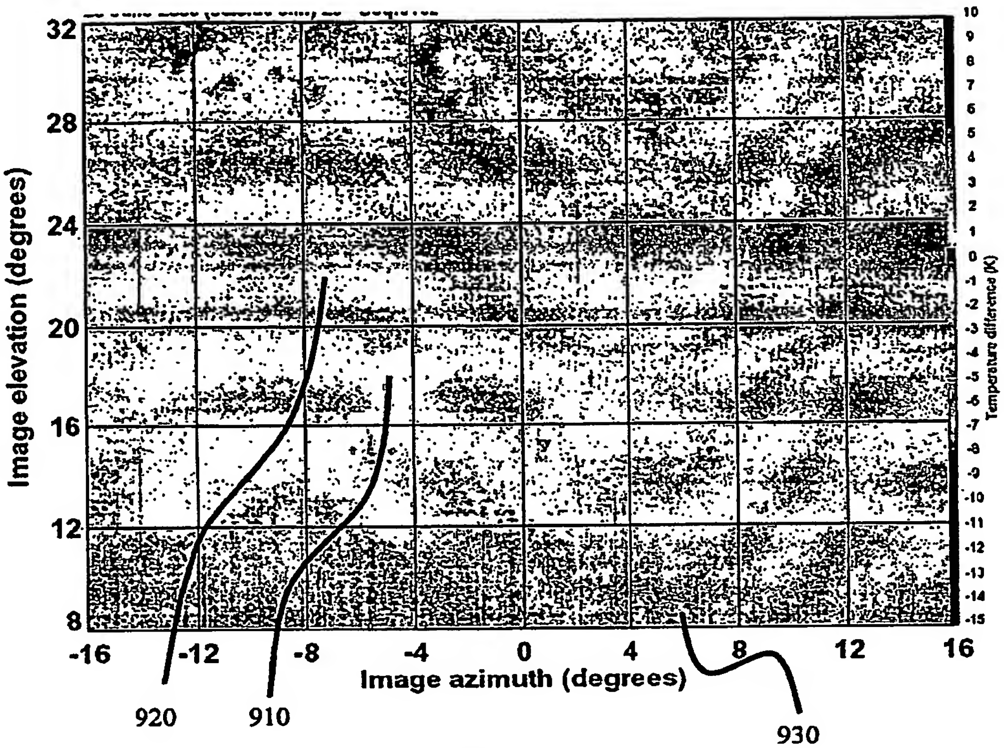

32
28
24
20
16
12
8
Image elevation (degrees)
-16
-12
-8
-4
0
4
8
12
16
Image azimuth (degrees)
Temperature difference (K)
920
910
930

FIG. 9

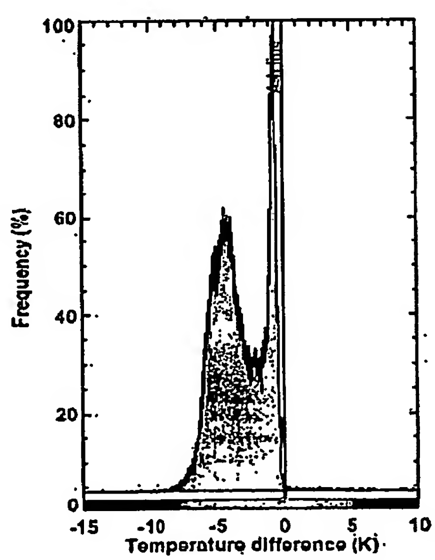

100
80
60
40
20
0
Frequency (%)
-15
-10
-5
0
5
10
Temperature difference (K)

FIG. 10

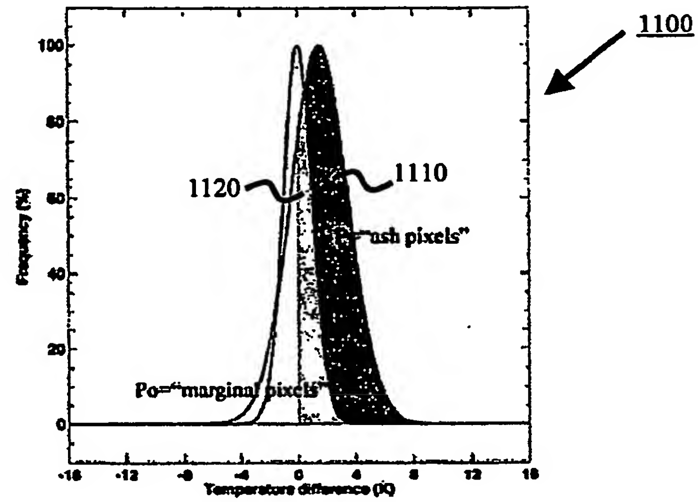

1100
1120
1110
"ash pixels"
Po="marginal pixels"
Frequency (%)
Temperature difference (K)

FIG. 11

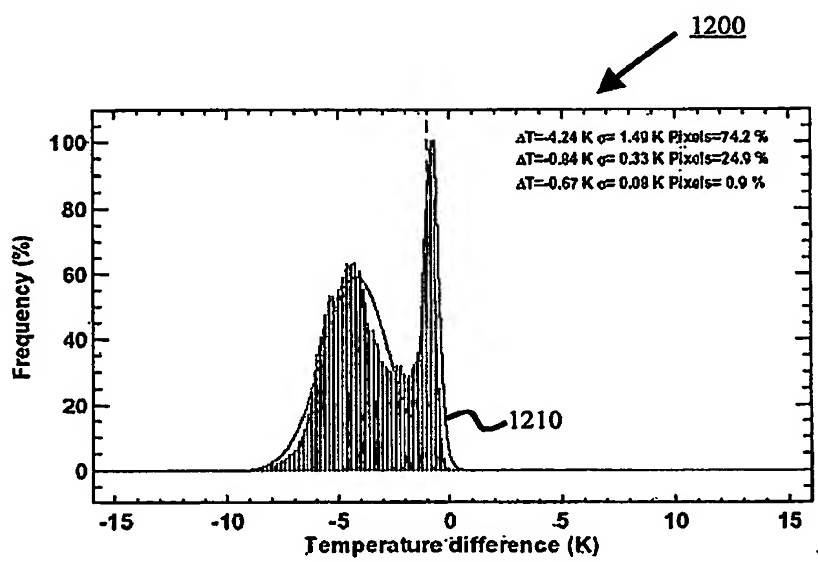

1200
ΔT=-4.24 K σ= 1.49 K Pixels=74.2 %
ΔT=-0.84 K σ= 0.33 K Pixels=24.9 %
ΔT=-0.67 K σ= 0.08 K Pixels= 0.9 %
1210
Frequency (%)
Temperature difference (K)

FIG. 12

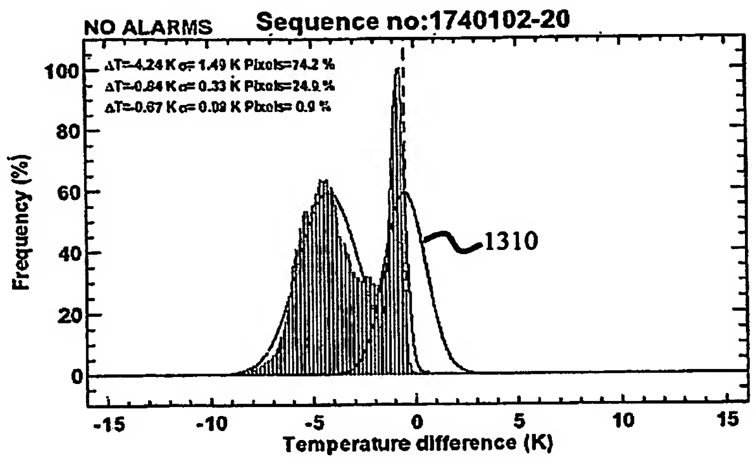

NO ALARMS
Sequence no:1740102-20
ΔT=-4.24 K σ= 1.49 K Pixels=74.2 %
ΔT=-0.84 K σ= 0.33 K Pixels=24.9 %
ΔT=-0.67 K σ= 0.09 K Pixels= 0.9 %
Frequency (%)
100
80
60
40
20
0
1310
-15
-10
-5
0
5
10
15
Temperature difference (K)

FIG. 13

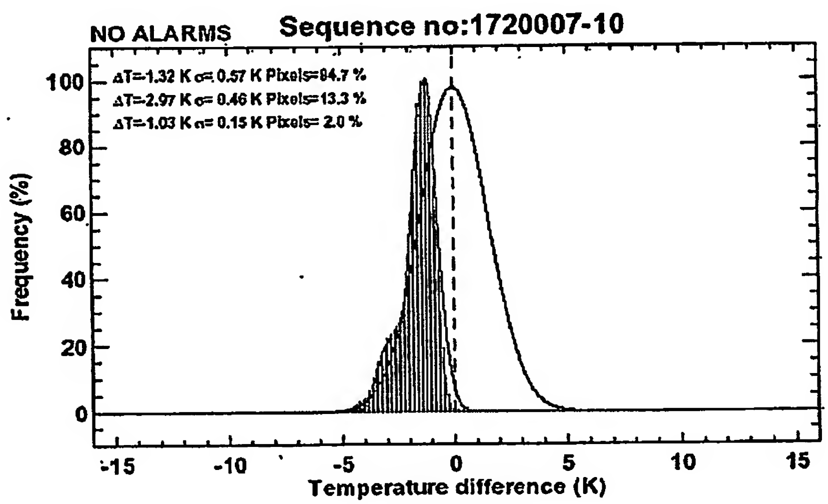

NO ALARMS
Sequence no:1720007-10
ΔT=-1.32 K σ= 0.57 K Pixels=84.7 %
ΔT=-2.97 K σ= 0.46 K Pixels=13.3 %
ΔT=-1.03 K σ= 0.15 K Pixels= 2.0 %
Frequency (%)
100
80
60
40
20
0
-15
-10
-5
0
5
10
15
Temperature difference (K)

FIG. 14

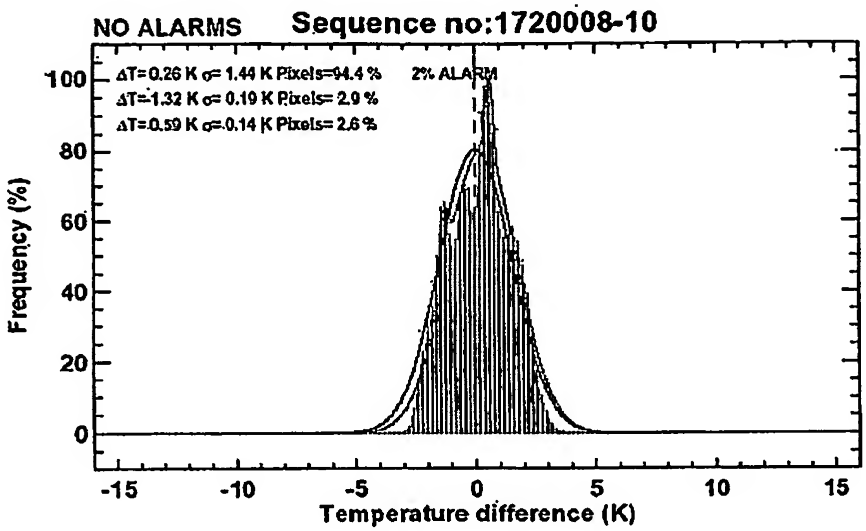

NO ALARMS
Sequence no:1720008-10
ΔT=0.26 K σ= 1.44 K Pixels=94.4 %
2% ALARM
ΔT=1.32 K σ= 0.19 K Pixels= 2.9 %
ΔT=0.59 K σ=0.14 K Pixels= 2.6 %
Frequency (%)
100
80
60
40
20
0
-15
-10
-5
0
5
10
15
Temperature difference (K)

FIG. 15

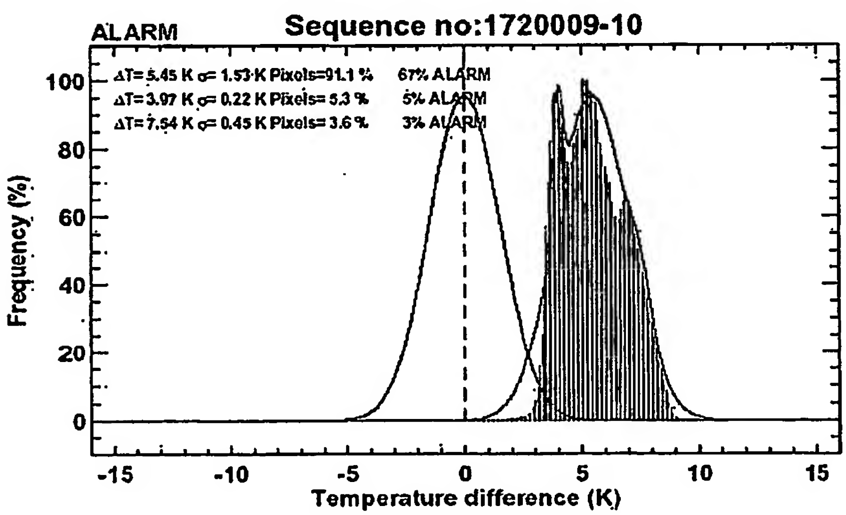

ALARM
Sequence no:1720009-10
ΔT=5.45 K σ= 1.53 K Pixels=91.1 %
67% ALARM
ΔT=3.97 K σ= 0.22 K Pixels= 5.3 %
5% ALARM
ΔT=7.54 K σ= 0.45 K Pixels= 3.6 %
3% ALARM
Frequency (%)
100
80
60
40
20
0
-15
-10
-5
0
5
10
15
Temperature difference (K)

FIG. 16

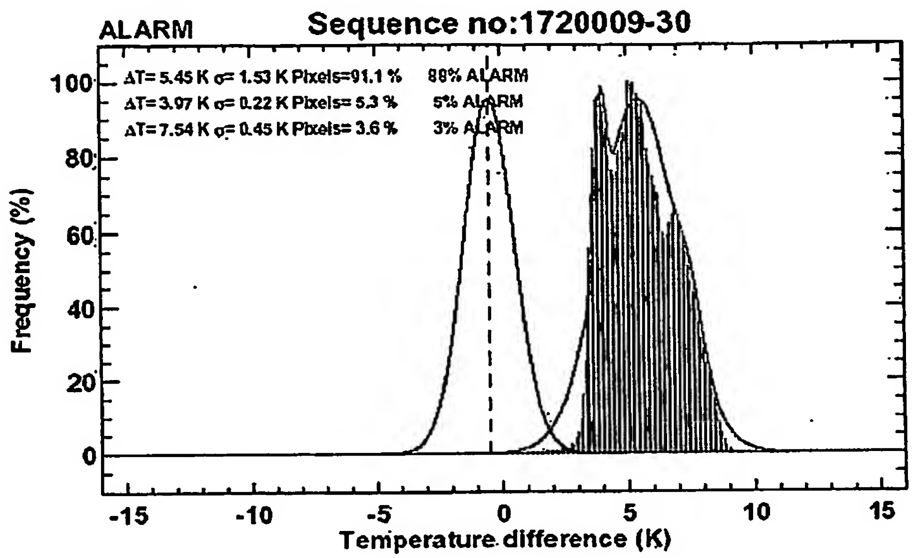

ALARM
Sequence no:1720009-30
ΔT= 5.45 K σ= 1.53 K Pixels=91.1 %
88% ALARM
ΔT= 3.97 K σ= 0.22 K Pixels= 5.3 %
5% ALARM
ΔT= 7.54 K σ= 0.45 K Pixels= 3.6 %
3% ALARM
Frequency (%)
100
80
60
40
20
0
-15
-10
-5
0
5
10
15
Temperature difference (K)

FIG. 17

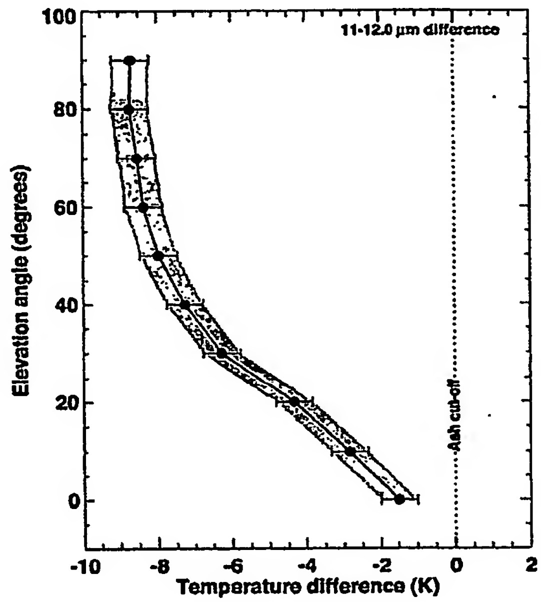


FIG. 18A

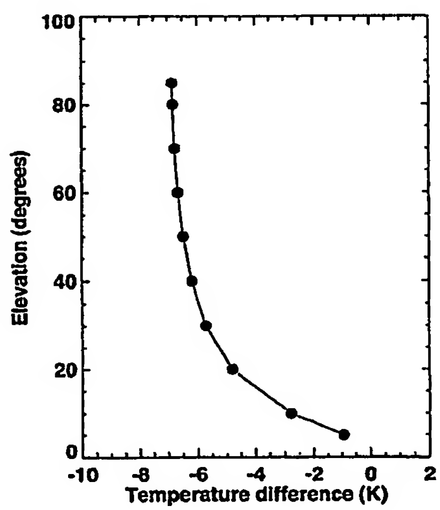


FIG. 18B

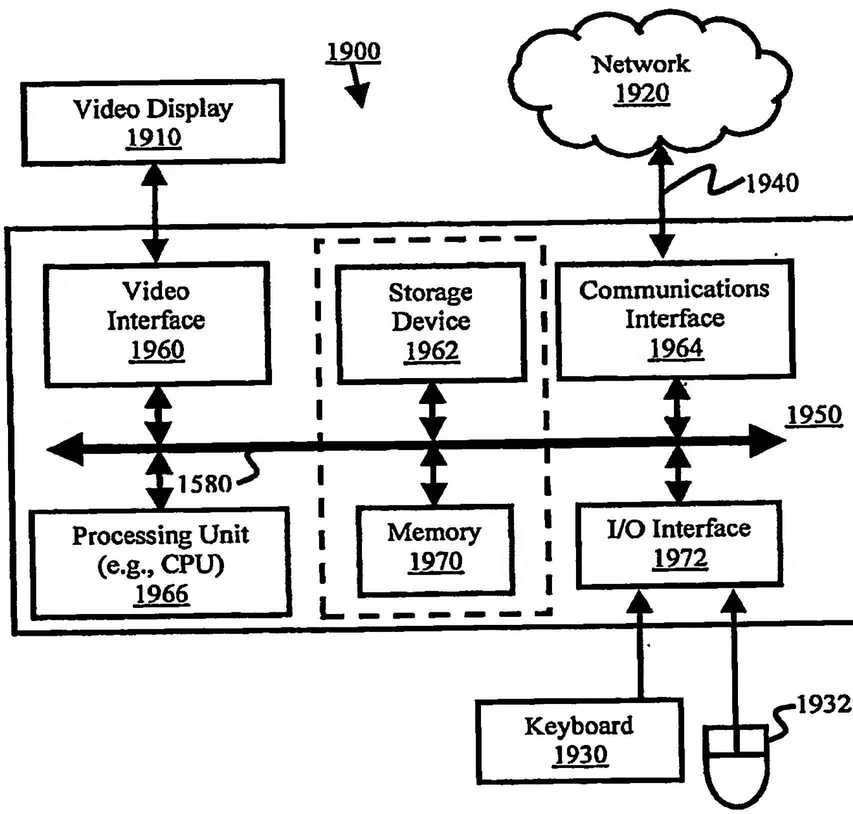

1900
Video Display
1910
Network
1920
1940
Video
Interface
1960
Storage
Device
1962
Communications
Interface
1964
1950
1580
Processing Unit
(e.g., CPU)
1966
Memory
1970
I/O Interface
1972
Keyboard
1930
1932

FIG. 19